DEVELOPMENT OF AN ELECTROTHERMOMECHANICAL XY MICROPOSITIONER

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Abstract. *The research regarding small object manipulation, mechanical or biological, has its importance increasingly evidenced by the world trend towards systems miniaturization. The micromechanisms that allow from teleoperation to complete automation in its use are called MEMS (Micro-Electro-Mechanical Systems), whose mechanical elements and actuators are made by microfabrication technology. Almost all of them are based on compliant mechanisms technology, whose mobility is given by their own structure compliance instead of using joints and pins which are hard to be made in the micro-scale. A simple type of actuation is called electrothermomechanical, based on the thermal expansion of the structure caused by an electrical current. The objective of this work is to study the complete development cycle of an electrothermomechanical XY micropositioner, including its simulation by finite element method (using ANSYS), its fabrication and development of the positioning command system (programmed in Matlab), implemented by using a remote controlled DC source with GPIB interface and a probe station with a CCD camera to monitor it. The complete system prototype (actuator and command system) was successfully implemented and tested at the Brazilian Synchrotron Light Laboratory (LNLS) at Campinas (SP). To reduce mechanical stresses and to increase maximum displacement, an investigation was conducted about the use of more than one material in the same mechanism.*

Keywords: *MEMS, microfabrication, compliant mechanisms, electrothermomechanical, electronic command*

1. Introduction

The research regarding small object manipulation, mechanical or biological, has its importance increasingly evidenced by the world trend towards systems miniaturization. Its main direct applications have a wide range, varying from assembly of mechanical systems with reduced size, to microsurgeries and biotechnology. Due to its large scale use, it is necessary to have a high accuracy under high positioning speed of the device.

Micromechanisms that allow from teleoperation to complete automation in its use are called MEMS (Micro-Elecrto-Mechanical Systems), whose mechanical elements and actuators are made by microfabrication technology. Almost all of them are based on compliant mechanisms technology, whose mobility is given by their own structure compliance instead of using joints and pins which are hard to be made in the micro-scale. A simple type of actuation is called electrothermomechanical, based on the thermal expansion of the structure caused by an electrical current, converting an electric input into a mechanical output (Ananthasuresh, 2003; Yin and Ananthasuresh, 2002; Sigmund, 001a,b; Mankame and Ananthasuresh, 2001). Among the designed electrothermomechanical MEMS, two of them have been more discussed in the literature: MEMS in open “V" format (Que et al., 1999; Park et al., 2000; Chu and Gianchandani, 2003; Chu et al., 2003) and the pseudo-bilaminars (Chen et al., 2002; Moulton and Ananthasuresh, 2001; Comtois et al., 1998). The open “V" will be the base for the present design.

The objective of this work is to study the complete development cycle of an electrothermomechanical XY micropositioner, including its simulation by finite element method (using ANSYS), its fabrication and development of the positioning command system (programmed in Matlab), implemented by using a remote controlled DC source with GPIB interface and a probe station with a CCD camera to monitor it. At the end, the complete system prototype (actuator and command system) was successfully implemented and tested at the Brazilian Synchrotron Light Laboratory (LNLS) in Campinas (SP). To reduce mechanical stresses and to increase maximum displacement, an investigation was conducted about the use of more than one material in the same mechanism.

This paper is organized as follows: in Section 2., it is explained the choices made for the type of actuation and material used; Section 3. gives an overview of finite element analysis in this work; Section 4. describes the microfabrication method used; Section 5. explains how the electronic command would be implemented; Section 6. shows the application of all techniques mentioned in the present work and the results obtained; finally, Section 7. concludes the work.

2. MEMS Preliminary Design

The microactuator will have two-dimensional actuation, handling objects within a plane. Due to its size (the biggest dimension is about 1cm), it will be a compliant mechanism, given the difficulty of manufacturing pins and joints in this scale. Compliant mechanisms have some advantages, as inexistence of slack and friction, however they are restricted to limited displacements as larger displacements could lead to high structure stress.

For its actuation, it could be chosen one of many available types, each one with its particular advantages and drawbacks. An ideal actuation should have enough power to actuate the compliant structure and still be able to do work on a desired load. It should also require simple electric controls and be easy to manufacture. Among many available types of actuation, none of them is clearly superior in any application. The actuator choice involves a compromise solution between desired characteristics.

In the present work, the electrothermomechanical actuator was chosen. Its functionality is based on volumetric expansion of the actuator material due to heating. Other possible types are the piezoelectric, capacitive and Shape Memory Alloy (SMA). To choose the actuation principle, three characteristics were analyzed: maximum performance (maximum possible displacement, force and work), manufacturing (ease of components fabrication and assembly of the mechanism) and versatility (use limitations of the mechanism). Comparing to the others, the electrothermomechanical actuators have large force and small displacement. It also presents a relatively large work density. Only common materials, such as nickel, are used in its fabrication and it does not need to have a low tolerance manufacturing, such as 1μm needed by the capacitive actuator. The electrothermomechanical actuators produce much heat, what makes its use prohibitive in thermally sensible environments. It also requires a relatively high-power source to work. Despite these drawbacks, the actuator command is simple and it has displacements linearly related to the input. As electrothermomechanical actuators depend on thermal effects (like SMA), it has a slower response compared to piezoelectric and capacitive atuators. Thus, the electrothermomechanical actuator is a good compromise solution between the above mentioned characteristics. Because of its high-power requirement mentioned above, this actuator cannot be used in many applications. However, it is acceptable in laboratories, where usually there are available sources that could satisfy this need.

The electrothermomechanical actuator is based on the thermal expansion of its own structure. The thermal expansion is the effect of expansion of a material under heating, characteristic presented by all solid materials in many degrees, and it is measured by the thermoelastic coefficient α. Displacement and force of the actuator vary linearly with the temperature difference ΔT considering a simple actuator, such as a bar fixed at one end and free at the other. In this work, the actuator used is called “active" because it has means to heat its own structure. This heating will happen due to electric resistance (Joule effect). Thus, by varying the difference of electric potential applied to the structure, the temperature difference ΔT can be controlled (Jonsmann, 1999).

The material used for actuator manufacturing is one of the factors that determine its main characteristics (free displacement and blocking force). The material properties considered are the expansion coefficient α and Young’s modulus E. For the case of thermal actuators, higher expansion coefficient α and Young’s modulus E are desired for higher possible displacements and force. Nickel and copper have high performance and they are similar. In order of preference, they are just behind aluminum, whose displacements are slightly higher and forces, slightly lower. Between nickel and copper, the main difference is a dynamic characteristic which will not be considered since the actuators are designed for quasi-static regime. The chosen material for the actuator manufacturing was nickel.

3. Simulation using Finite Element Method

For analysis of electrothermomechanical mechanism, there are three types of fields working together: electrical, thermal and elastic fields. Thus, a complete analysis must be conducted in three steps: the electrical part solves the electrical current distribution in the structure; the thermal determines the temperature in each point of the device due to heating by Joule effect and heat losses by thermal conduction, convection and radiation; the elastic defines the mechanism displacements due to temperature distribution.

Each type of field could be solved separately (electrical, thermal and elastic fields, in this order) if there are no kind of coupling among them. In this work, this coupling is caused by the variation of the material properties with temperature, what demands a simultaneous solving of the electrical, thermal and elastic analyses. The differential governing equations of each type of field are stated in Sigmund (001a). The analyses were done using the finite element software ANSYS.

4. MEMS Fabrication

The MEMS in discussion were manufactured using a kind of surface micromachining. In this process, the substrate remains inaltered, and thin layers are added or removed building a desired pattern over the substrate surface. This technique gives a great flexibility in obtaining two-dimensional structures, however with less control over thickness.

The main process used was the lithography, technique to obtain a desired pattern in deposed films, adding or subtracting successive layers. There are many kinds of lithography, including the photolithography, that uses ultraviolet (UV) radiation, the deep ultraviolet (DUV) and lithography by X-ray. The photolithography is cheaper and, so, the most common in industry and it was the method used in this work. The other process, that differs only in the method of exposure, have a better resolution than the photolithography.

In the photolithography used, a uniform layer of photoresist is deposed over an electrical conductive substrate. The photoresist is an organic compound sensible to light that can be classified as positive, when a radiation exposure makes it more soluble, or negative, when the radiation makes it less soluble. The uniform layer of photoresist, along with the right mask which contain the pattern to be formed, is exposed to a controlled dose of UV radiation. Next, the more soluble parts of the photoresist are removed with a solvent, obtaining the desired pattern over the substrate. The electroplating of the chosen metal is done to fill the formed pattern. The non-sensibilized photoresist is removed with a solvent. Repeating this process for each metal layer to be deposed, the complete mechanism is formed.

5. MEMS Command

The electrothermomechanical MEMS command, as mentioned before, was based on a electrical potential reference by a DC source. It can be done remotely by an user interface implemented in a computer.

Figure 1 shows an overview of the strategy used for the remote control of the DC source and the information flux needed for command implementation.

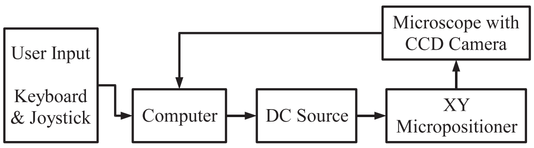


Figure 1. DC source remote command overview

The user interacts with the system to obtain the desired micropositioner displacement through keyboard or joystick. By keyboard, the value of the electric potential applied for the desired displacement is input, and by joystick, the direction and magnitude of the displacement are input. These informations are sent to a computer that processes the data that will be delivered to the DC source. The DC source, with the data, provides the right potential to microactuator. The displacement done is observed by a microscope whose image is captured and displayed by a computer. The software and hardware interfaces between the components of the remote command system are shown in Fig. 2

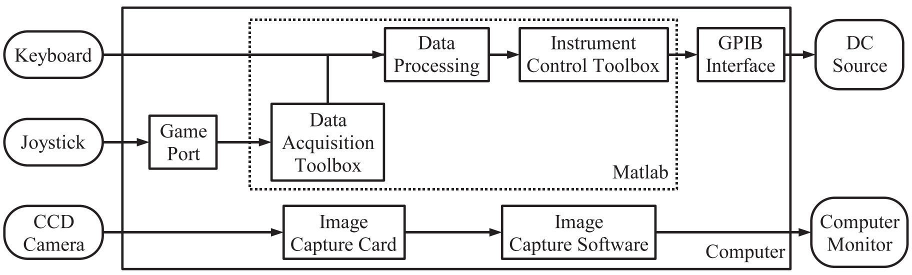


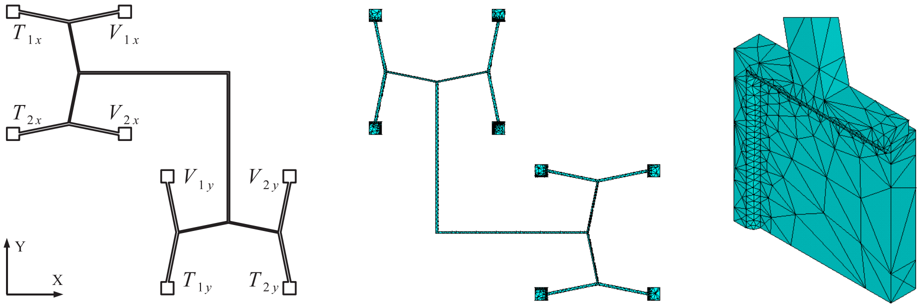
Figure 2. Hardware and software interfaces

The platform used for data processing was Matlab. It can receive information given by user through two interfaces: keyboard, for which Matlab already has data reading methods; joystick, connected to game port (analog input) of the computer. To receive data from the joystick, it will be used “Data Acquisition Toolbox" from Matlab, whose functionality allows comunication with data acquisition devices. The joystick data processing performed by Matlab means to translate the desired displacement into an electric potential to be sent a DC source as a command for the microactuator. The communication between computer and DC source is provided by GPIB interface, and the processed data are available at this interface through the use of “Instrument Control Toolbox".

The microactuator displacements are watched by a microscope with a CCD camera attached. The images are captured by an image capture card and the image processing (to record movies and take pictures) is done by a commercial software.

6. Results

The main focus of study of this paper is the XY micropositioner, whose design was based on literature, composed by open “V" actuators and displacement amplifiers. The structure of each axis actuator is presented by Park et al. (2000) (Fig. 3(a)). It has two similar structures for the actuation in X and Y directions. The actuation is based on thermal expansion of its own structure when it is heated by Joule effect. On the pairs of terminals V_{ix}-T_{ix} and V_{iy}-T_{iy} (where $i = 1$ or 2), an electric potential difference are applied to induce current to heat them, generating an expansion. The combination of two actuations in a single axis, be it X or Y, generate a displacement that is amplified and actuate the rod in the right direction. Each axis structure of the micropositioner have dimensions of 2.7×2.5mm (delimited by the terminals), without considering the rod (3mm long). The mechanism has a thickness of 45μm and is fixed on the alumina substrate by the terminals. There is a distance of 13μm between the substrate and suspended parts of the mechanism.



(a) Scheme (b) Complete ANSYS model (c) ANSYS model detail

Figure 3. XY micropositioner – Scheme and ANSYS model

6.1 XY Micropositioner Simulations using Finite Element Method

As mentioned before, the mechanism simulations were done using ANSYS, a finite element software. For the simulation of the mechanism, there must be a CAE model. With a CAD model available, it was easy to have a CAE model for the finite element simulation software. As electric potentials are applied, the most important informations from the simulations are: total current consumed (that cannot be higher than a maximum allowed by the DC source), temperature distribution (that defines the displacement and cannot be high enough to damage the structure) and the structure displacements. Also, it is important to know the maximum stress to verify the feasibility of displacement of the compliant mechanism.

As boundary conditions, it was defined null displacements in all axis (X, Y and Z) and temperature of 293K for the terminals, fixed on the substrate. In all areas exposed to the environment, it was imposed a convection coefficient of 33.000W/m^2·K (and environment temperature of 293K). The only areas where there was no convection were the areas in contact with the substrate. To generate the displacements, it was imposed an electric potential of 2V on the V terminals of only one axis, connecting the reference (ground) level at the T terminals of both axis.

The ANSYS model, discretized in 7687 elements, is shown in Fig. 3(b) and 3(c) with one of its terminals detailed. The simulation were done considering an actuation on the X axis.

The nickel properties considered for the simulation are presented in Tab. 1 and 2. This new properties for the nickel were obtained from experiments conducted at the Brazilian Synchrotron Light Laboratory (LNLS) in Campinas (SP) with micromechanisms specially designed for these characterizations.

As a result from the simulation, the currents at the terminals T_{1x} and T_{2x}, close to the V terminals where the 2V potentials were applied, were about 1.96A. At terminals T_{1y} and T_{2y}, the simulated currents were about 94mA. At terminals V_{1x} and V_{2x}, the total current was 4.1A. The potential applied was considered as the maximum that should be used experimentally since the maximum temperature (596K OR 323^{o}C) was near 350^{o}C, that is usually the limit for electroplated nickel electrothermomechanical MEMS (Que et al., 2001). The displacement was 60μm and the maximum stress (Von Mises) was 932MPa, higher than the yield tensile strength of electroplated nickel (Fritz et al., 2000) and even the ultimate tensile strength for the typical nickel (317MPa). It indicates that the actuation would lead to permanent damage of the structure in the first instants of use, degrading its performance and funcionality, and it could even happen a structural failure. However, the application of 2V was used at the experiment without any failure, what will be discussed further.

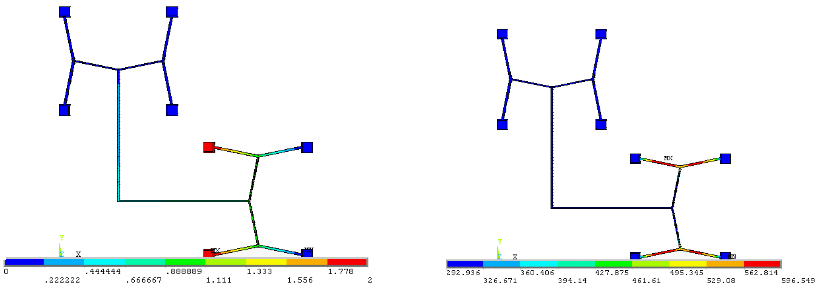
To obtain larger displacements and smaller stresses, the XY micropositioner was changed in a way that copper, with a lower Young’s modulus, was used in regions of largest deformation and stress. These points with largest stress are in the middle of the displacement amplifiers (the “V" structure between the two actuators in each axis structure). Thus, the copper parts are the two displacement amplifiers, keeping the four open “V" actuators, rods and terminals in nickel (Fig.

Table 1. Some electroplated nickel properties

Properties	Values
Density	8,890kg/m^3
Young's modulus	188GPa
Poisson coefficient	0.31
Thermal expansion coefficient	1.34×10^{-5}K^{-1}
Electrical Resistance	$1.71\times10^{-6}\Omega\cdot$m (at 293K) $9.31\times10^{-7}\Omega\cdot$m (at 298K) $9.49\times10^{-7}\Omega\cdot$m (at 500K)

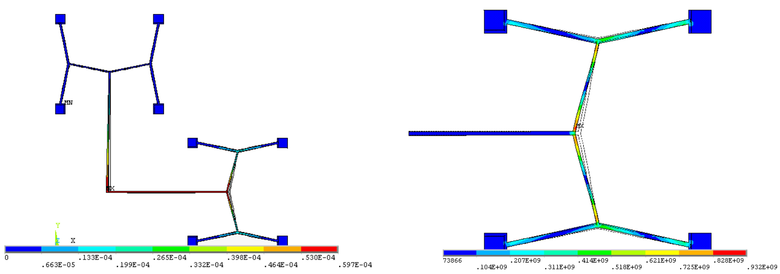
Table 2. Temperature and Thermal conductivity for electroplated nickel

Temperature (K)	Conductivity (W/m·K)
250	97.5
300	90.7
350	85.0
400	80.2
500	72.2
600	65.6
800	67.9
1000	71.8
1200	76.2
1400	80.4



(a) Potential distribution (b) Temperature distribution

Figure 4. XY Micropositioner Simulation



(a) Displacements (b) Stress (Von Mises) (detail)

Figure 5. XY Micropositioner Simulation

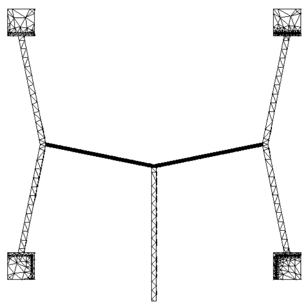


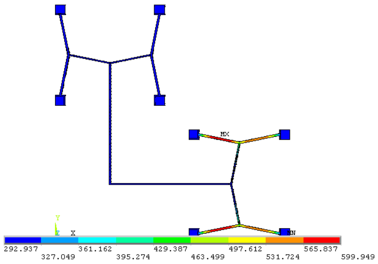
Figure 6. XY micropositioner with two materials (white: nickel; black: copper)

6). With the same boundary conditions, element types and discretization, simulations were done for the new model.

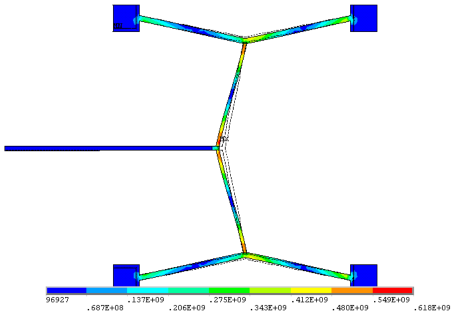
The total consumed current (passing through V_{1x} and V_{2x}) was almost the same, about 4.2A. The terminals T_{1x} and T_{2x} currents, close to the point of application of electric potential, were about 1.95A each. At T_{1y} and T_{2y}, the simulated currents were about 130mA. The temperature distribution has not changed so much, with a maximum of almost 600K (327$^{\text{o}}$C). It can be noticed that a non-uniform heating at the open "V" actuators (difference about 10% from one side to another) emphasizes the amount of current passing to the Y axis terminals. It happened because of the electrical resistance reduction between the points of application of potential (V_{1x} and V_{2x}) and the Y axis grounded terminals (T_{1y} and T_{2y}), given that copper is a better electric conductor than nickel. Despite the displacement (less than 61μm) has not changed significantly (an increase of less than 2%), the maximum stress (Von Mises) was 618MPa, a reduction of more than 33%. Even with this reduction, this stress is still much higher than the ultimate tensile strength of annealed copper of 210MPa, showing a high probability of failure, like the previous case.

6.2 XY Micropositioner Fabrication

In this work, an alumina substrate was used. As alumina is not an electrical conductor, titanium and gold was deposed by sputtering over the substrate to allow the electroplating process. This titanium/gold layer must be removed after the



(a) Temperature distribution



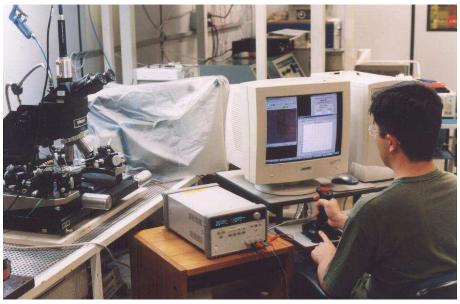
(b) Stress (Von Mises) (detail)

Figure 7. XY Micropositioner (two materials) Simulation

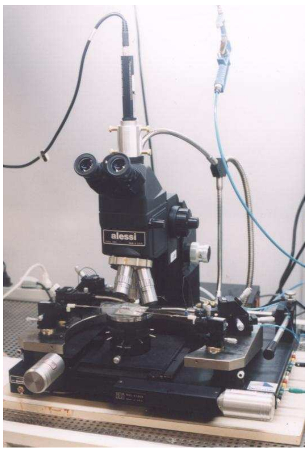
whole process not to short-circuit the mechanism terminals. To allow mechanism motion, some portions must not be in contact with the substrate. Thus, in these areas, a sacrifice layer was deposed. A sacrifice layer is that layer deposed just to create a geometry, being removed after the process. The metal of this layer was copper, since its chemical removal has a good selectivity when considering nickel. In other words, it can be chemically removed without affecting significantly the nickel layer. The mask used for the UV exposure was a common photolith ordered from a graphic services company.

6.3 XY Micropositioner Experimental Characterization

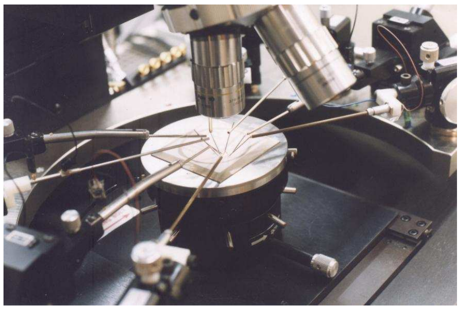
The experiments with the manufactured mechanism were done to verify the simulated data and to test the microactuator command. The fabrication and tests were carried on at the Brazilian Synchrotron Light Laboratory (LNLS), since its Microfabrication Laboratory has all the equipment to observe the displacements of the micropositioner by using a CCD camera attached to a probe station, with $100\times/200\times/400\times$ magnification (Fig. 8(b)). The substrate with the micromechanism was fixed to the probe station by vacuum and the tungsten probes were used for the application of electric potentials at the micropositioner terminals. The potentials were provided by a DC source that displays the current at the output. The substrate, probes and their supports are shown in Fig. 8(c).



(a) Complete Set



(b) Microscope with CCD camera

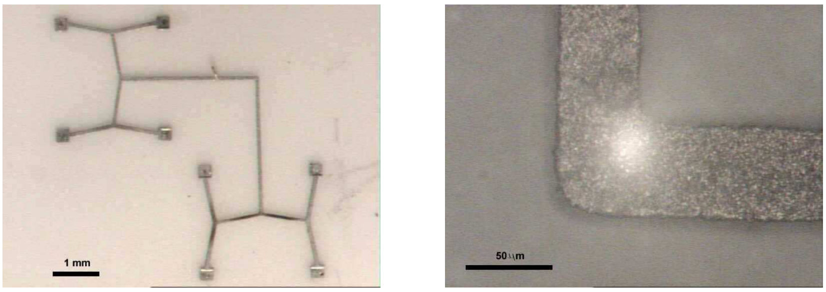


(c) Substrate and probes

Figure 8. Equipment set for operation of XY micropositioner by joystick

The images were captured and analyzed by a computer with an image capture card and a software that allowed the displacement measurement. The other simulation data (temperature distribution and stress) could not be determined by the experiments with the available equipment. The complete set of equipments used for the remote command of the micropositioner are illustrated in Fig. 8(a). The micropositioner manufactured is shown in Fig. 9(a). The joystick could be used as planned and the computer applied the potentials at the terminals of the micropositioner according to the command given. The tip of the rods from the structures of X and Y axes could be visualized in real-time through the computer monitor. It can be viewed in Fig. 9(b), captured with a magnification of $200\times$. In Tab. 3, there is a summary of the experiments made, where each half of one axis actuator (set 1 or 2 of terminals V and T) were actuated individually and together with a potential of 2V.

One can notice a large difference between the simulated displacement and the displacement obtained in the experiment. The experimental one, in the best case (Y axis actuation), achieved 26μm, less than a half of 60μm in the simulation. There



(a) Complete (b) Mechanism tip

Figure 9. Manufactured XY micropositioner

Table 3. Experimental results

Actuated structure		Electrical Current (A)	Displacement (μm)
X axis	1	1.440	5.12
	2	1.490	3.82
	1 and 2	1.890	5.97
Y axis	1	1.550	5.50
	2	1.550	9.00
	1 and 2	1.225	26.44

were also differences in the current measured when applying 2V at the pairs of terminals: experimentally, the current in each pair of terminals was about 1.5A, a smaller value than in the simulation (2.1A). Additionally, the sum of currents of the individual actuation of the two halfs is different of the current consumed when the axis structure is completely actuated. These divergences can be a result of the differences between the values of electrical resistance and thermal conductivity used in the simulation and the values found in the nickel material of the structure. The material properties could also be changing by heat during the experiment. Another factor that could be responsible for these differences is the convection coefficient adopted in ANSYS model. It must be noted that the mechanism temperature achieved its upper limit, since there were a quick oxidation as observed by Que et al. (2001) and it is visible in Fig. 9(a) (darker parts of the structure). In other words, experimentally the structure had a temperature higher than in the simulation, even with a current of 1.5A instead of 2A.

By the same table, the displacement is decreased in the X axis instead of being amplified, with a total displacement of 9μm becoming smaller than 6μm, and there is a strong assimetry between the displacements when actuating both axes. They can be explained by fabrication issues and structures singularities that could induce an unexpected bending of the structure (out of the plane) or even result in different electrical and thermal properties of each axis structure.

When testing displacements of the X axis, the displacement was 10^{o} away from the expected direction. As it was 10^{o} away from the Y axis, it could indicate a little undesired actuation by the Y axis structure. This undesired actuation can be due to the grounded terminals of Y axis during the actuation of X axis, what would allow a flux of electrical current in the Y axis structure.

Another curious fact was that the XY micropositioner has not failed since the simulation pointed to a maximum stress much higher than the yield tensile strength of the electroplated nickel. There were a much smaller displacement, already discussed, that could explain a possible decrease in the stress. This decrease could be enough not to cause a failure in the mechanism.

A delay of about half second in the micropositioner response were detected. A response time of this magnitude was expected due to the principle of actuation based on thermal expansion. This delay cannot be attributed to the processing time of the Matlab software, since the DC source had indicated the desired potential in the same instant the command was given through the user interface (by keyboard or joystick). For a faster reaction, it would be also necessary to have control over the cooling process of the micropositioner, due to mainly convection that would be decreased in the actuation and increased when it stops.

7. Conclusions

In this work, the complete cycle of electrothermomechanical MEMS design was studied, including a remote command by joystick. The electrothermomechanical MEMS analyses were done using finite element method to obtain an estimation about the feasibility and behavior of the mechanism. Relatively cheap techniques of microfabrication were used (photolithography using common photoliths) and it resulted in a structure that allowed the remote command by joystick.

The divergences between simulation and experimental data were found and they could be minimized through more precise parameters of experiment conditions, such as electrical and thermal properties of electroplated nickel. As a future work, the electroplated nickel properties and the environment convection could be characterized to have a simulation close to reality.

The use of an additional material in the structure was investigated as an attempt to increase displacement and decrease structure stress. The reduction of the maximum stress was achieved, however the properties of the added material (copper) still indicates a high probability of structural failure. The selection of a material with a higher yield tensile strength and lower Young's modulus to substitute copper would allow the same displacement with a lower risk of failure.

8. Acknowledgements

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